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Holographic Aids for Internal Combustion Engine Flow Studies

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HOLOGRAPHIC AIDS FOR INTERNAL COMBUSTION ENIGNE FLOW STUDIES

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SUMMARY

Worldwide interest in improving the fuel efficiency of internal combustion (I.C.) engines has sparked research efforts designed to learn more about the flow processes of these engines. The flow fields must be understood prior to fuel injection in order to design efficient valves, piston geometries, and fuel injectors. Knowledge of the flow field is also necessary to determine the heat transfer to combustion chamber surfaces. Computational codes can predict velocity and turbulence patterns, but experimental verification is mandatory to justify their basic assumptions.

Due to their nonintrusive nature, optical methods are ideally suited to provide the necessary velocity verification data. Optical systems such as schlieren photography, laser velocimetry, and illuminated particle visualization have been used in I.C. engines, and now their versatility has been improved by employing holography. These holographically enhanced optical techniques are described in this paper, with emphasis on their applications in I.C. engines.

INTRODUCTION

Internal combustion engines are used widely in a variety of land vehicles and small aircraft. Emphasis is being placed on learning the details of the combustion processes in these engines in order to optimize their fuel efficiency. The first step towards understanding combustion is understanding the cold flow of air through these engines. Knowledge of the air flow is the first step in predicting flame front travel, fuel mixing, and heat transfer between surfaces. Computer codes have been developed to calculate the behavior of the flow, but these codes are only as good as their assumptions and must therefore be verified experimentally.

This paper will describe how holography can be used for flow diagnostic studies in I.C. engines. It should be understood that these diagnostics can be used for many other applications as well, for example, turbine and compressor cascades, propeller wakes, and combustion can be studied with some or all of the techniques to be described in this paper.

There are two types of techniques used in I.C. engine flow field studies: point measurements and visualizations of large sections of the flow field. Flow visualizations provide information about the qualitative nature of a flow, while precise quantitative data is obtained through point measurements. It is often helpful to know the qualitative trends of a flow before proceeding on to point measurements in order to concentrate attention on those areas of the flow which exhibit the most change.

Optical techniques can be used for the acquisition of both types of data. The invention of the laser has led to new optical diagnostic techniques. Lasers can be used as the light source for traditional techniques such as schlieren photography, as well as for previously impossible measurements which rely on the coherent nature of laser light, such as laser Doppler velocimetry. Laser beams can be focused down to spots as small as 10^{-6} mm^3, providing fine spatial resolution for point measurements. An additional advantage of using laser light is that holographic techniques can be readily applied, the main requirement for holography being the presence of coherent light.

Holography may be used to correct problems associated with optical measurement techniques. The main drawback to optical diagnostics in I.C. engines is that the flow under study must be optically accessible, requiring a window into the flow. It is generally better to have separate windows for light entrance and exit through the flow because measurement signal-to-noise ratios can be up to one thousand times worse when the light must retrace its path through just one window. Accurate measurements using conventional optical methods require windows that are optically flat, because curved or rough surfaces cause errors due to refraction and reflection.

This constraint has led to some interesting engine configurations. A widely used approach has been to modify the internal geometry of the engine and mount optical parts in the head (ref. 1). L-head engines equipped with windows above the piston and valves allow a full view of the combustion chamber (ref. 2). Optical access through the head provides good flow visualization pictures, but point data must be collected in backscatter with the attendant low signal-to-noise ratios. Forward scatter measurements require access through the wall. The light can enter through the head and exit through a small port in the wall, (ref. 3) or pass solely through wall surfaces. To avoid aberrations caused by the cylindrical surface of the combustion chamber, square pistons (ref. 4) or index of refraction matching fluids (ref. 5) have been used. Instead of altering the flow by using nonstandard engine configurations to avoid cylindrical wall aberrations, techniques have been developed which use holography to counteract the effect of the curved wall (refs. 6 and 7). This allows flow studies in engines such as the axisymmetric motored engine shown in figure 1 (ref. 8).

Another reason for using holography in conjunction with conventional optical systems is versatility. One hologram can be recorded, and then several diagnostic methods can be applied to the recorded flow to extract more information than a single test can provide. These benefits will be shown more clearly in the specific appications that follow. First, however, a general description of off-axis holography will be given.

DESCRIPTION OF HOLOGRAPHY

A hologram is an interference pattern recorded on a piece of high resolution film. The interference pattern is created by splitting a single coherent light beam into two parts, allowing one part to travel directly to the film while the other illuminates the object to be recorded. Some of the scattered light from the object (the object wave) will arrive at the film to interfere with the undeviated light (the reference wave). Figure 2 shows a typical lay-out.

The interference pattern created by the object and reference waves consists of a very fine pattern of light and dark regions. It can be recorded on a gelatin film sensitized in ammonium dichromate solution. The light is absorbed by the Cr^{+6} ion in the film and causes a decay to a Cr^{+3} ion. During development, the Cr^{+3} ions form cross-link bonds with the gelatin, while the unexposed Cr^{+6} ions do not (ref. 9). This causes variations in the index of refraction of the film, and the pattern of these variations uniquely describes the object that was recorded. The three-dimensional information is retained because both the amplitude and phase of the light off the object contributed to creating the interference pattern. In white light photography, all phase information is lost so only two dimensions are recorded.

The processed film is viewed by illuminating it with a beam identical to the reference wave. This light interacts with the index of refraction variations in the hologram and reproduces an exact image of the original object (fig. 3). Other images may be formed also, but only the identical replication is of interest here.

The specific applications of holography in internal combustion engine diagnostics that follow are divided into two categories: point measurements and flow field visualizations.

POINT MEASUREMENTS

Three-dimensional velocity measurements at a point can be made using laser Doppler velocimetry (LDV). This technique relies on the formation of interference fringes when two coherent light beams cross. To measure one component of velocity, a laser beam is split in two and recombined at an angle. Fringes are formed where the beams cross, and the distance between the fringes is a function of the wavelength and the angle at which the beams cross. For engine studies, the beams are crossed somewhere in the combustion chamber and small particles are introduced in the air flow. These particles should be of uniform size, small enough to follow the flow, and large enough to be detected.

Some of the particles cross the measurement volume and emit a frequency of scattered light that is proportional to both the fringe spacing and their velocity component normal to the fringes. This frequency is detected by a photomultiplier tube which converts the light frequency into an electrical signal. The electrical signal is processed and fed into a computer where the velocity is calculated and displayed to the user. All three velocity components can be obtained in this manner, providing that some distinguishing feature is attached to each component for later identification. Different colors, different polarizations, or shifted fringe patterns may be used for component differentiation.

Since the beams must cross each other at an angle to produce fringes of finite width, problems arise when the container of the flow under study is not flat. Each beam will refract a different amount due to the difference in the thickness of the glass at each point. The two beams may still cross; however, the crossing point will no longer coincide with the beams' focal waists (fig. 4). If more than two beams are used they will not all cross at the same point if a single conventional focusing lens is used. The relative misalignment is most severe with thick containers made of materials with a high index of refraction.

The holographic element described in reference 6 will correct aberrations caused by any arbitrarily shaped transparent container. A mirror system is set up to bring any number of beams into coincident focus through the top of a container (fig. 5). A hologram is then made using the focused point as the object, with a reference beam brought around the side. The hologram may then be reilluminated to produce the crossed beams inside the container without using the unwieldly mirror set-up. Although each set of focused beams within the container requires a unique set of holograms, each set can be made small so that many holograms can be recorded on a single sheet of film to produce many points in coincident focus.

A similar process can be used for collecting the scattered light. Instead of producing a point of light, it is desired to collect scattered light which has not been deviated by the spherical surface. A hologram is made using the point inside the cylinder as the object and a reference beam is again brought around the side. During data collection, some of the light scattered from the point will arrive at the hologram and recreate the reference beam. The roles of object and reference waves have been reversed to create the desired effect. This recreated "reference" beam is free from spherical aberrations, and can be directed to the photomultiplier tube. A collimating lens can be placed between the hologram and the cylinder to collect more scattered light. Figure 6 shows a schematic of the system.

Any method that relies upon crossing light beams to make a point measurement can use this holographic technique. There are many such methods being used in I.C. engines, such as: (1) gas velocity measurements made with LDV or laser transit anemometry; (2) species concentrations and temperatures in combusting gases determined by Raman scattering, Rayleigh scattering, absorption spectroscopy, or fluorescence spectroscopy.

By allowing each of these measurements to be made inside of a circular cylinder, the holographic technique just described can greatly extend the usefulness of each one of these powerful techniques.

FLOW FIELD VISULAIZATIONS

One method of flow visualization that has been used for years is to simply add particles to flow, illuminate them, and view their motion. Smoke, oil, and even baby powder (ref. 10) have been used as the particulate. Illuminating the entire flow volume only gives accurate information about the flow surface because individual planes within the chamber can not be distinguished from one another. For this reason, a thin plane of light may be used so that a single plane of flow can be resolved. Laser light is well suited for this purpose because a very thin sheet of light can be formed at high power levels. The high light intensity can expose a sheet of photographic film very quickly to provide stop-action photography of high speed flows. Two exposures can be made in rapid succession and the travel distance of the particles will give a rough estimation of their speed in that plane.

A curved surface will present the same problems as encountered in the LDV application - light passing through the curve will be refracted in undesireable ways. A multifaceted holographic element has been developed that is similar to the hologram designed to bring beams to coincident focus.[11] This hologram can provide the necessary aberration correction over an entire surface.

Another flow visualization technique is schlieren photography. It too, has been around for a long time, but holography has added more versatility.

Schlieren photographs render visible density gradients in a flow. The underlying principle is that density gradients cause gradients in the index of refraction of a fluid, which in turn deviates light passing through it. A standard system is shown in figure 7. The distinguishing feature of a schlieren system is the knife edge placed near the focal point of the second mirror. If there were no disturbances in the flow field, the intensity of the light striking the camera would depend only on how much of the beam the knife edge blocks. A flow with density gradients in it will cause the passing light to be deflected. This light will be diverted so that it either gets blocked by the knife edge, causing a dark area on the camera, or avoids hitting the knife edge, causing a bright area. The knife edge may be adjusted to provide higher contrast.

The major drawback to this technique is that the light is integrated along the entire field, obscuring information from individual planes in the flow. Multiple light sources and knife edges may be used to focus on a single plane, (ref. 12) but alignment is difficult and each plane must be photographed separately, eliminating temporal correlation between planes.

A solution to this problem can be obtained by making a hologram of the entire flow field. When the hologram is processed, it can be reilluminated to serve as the flow field for schlieren analysis. Now the knife edge can be positioned for optimum contrast at one's leisure, without worry that the flow will change. In addition, the single-plane schlieren methods may be employed for as many planes as is desired, without loss of temporal correlation, for a truly threedimensional analysis. Furthermore, the flow field is no longer limited to examination by just one technique. The same hologram can be used for shadow-graphy and interferometry. The former method will yield qualitative information on the second derivative of the density, while the latter will give direct quantitative density data (ref. 13).

CONCLUSIONS

There are two types of measurements that can yield information about a flow: point measurements and flow visualization. Both of these categories of measurements can be enhanced by using holography. Holography can assist in point measurements by allowing measurements to be made in any shape of vessel, and holography can help flow visualization by capturing the entire three-dimensional flow field at an instant for later interrogation by other methods.

The combined use of point and field measurements will provide extensive data on the flow inside an internal combustion engine. This data will be extremely useful in modifying computer codes and performing optimization studies to maximize fuel efficiency.

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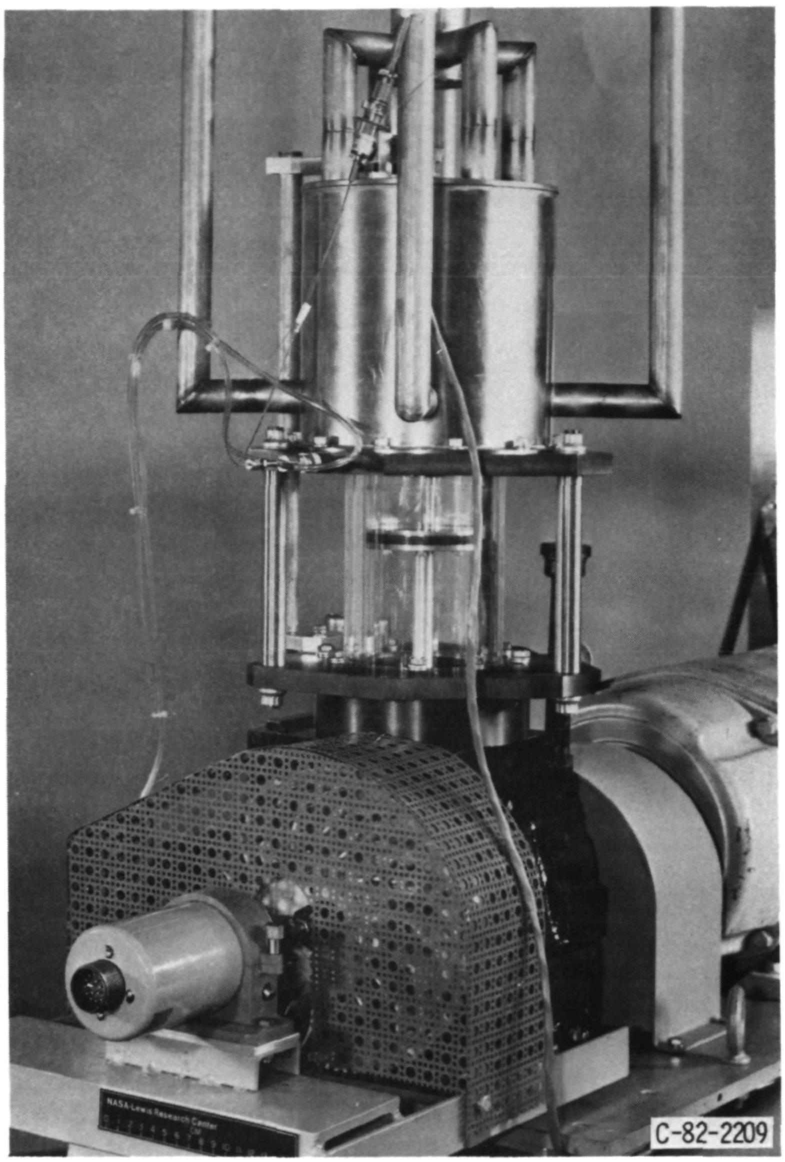

Figure 1. - Axis Y metric engine bore optical diagnostics.

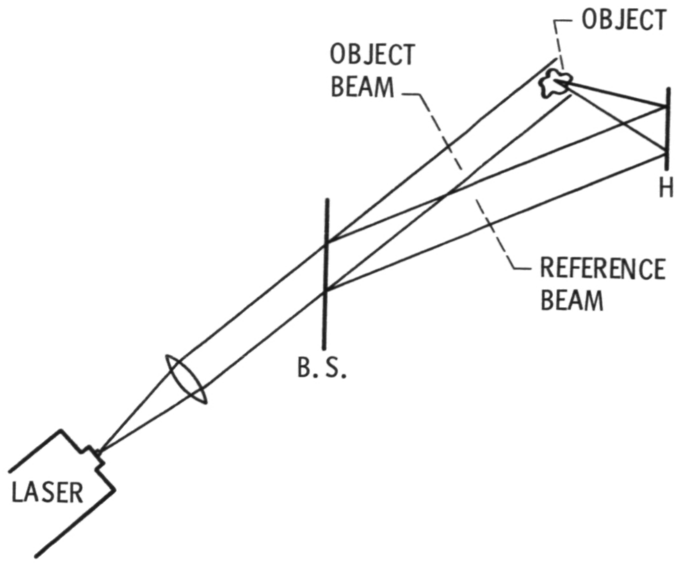

Figure 2. - Recording a hologram.

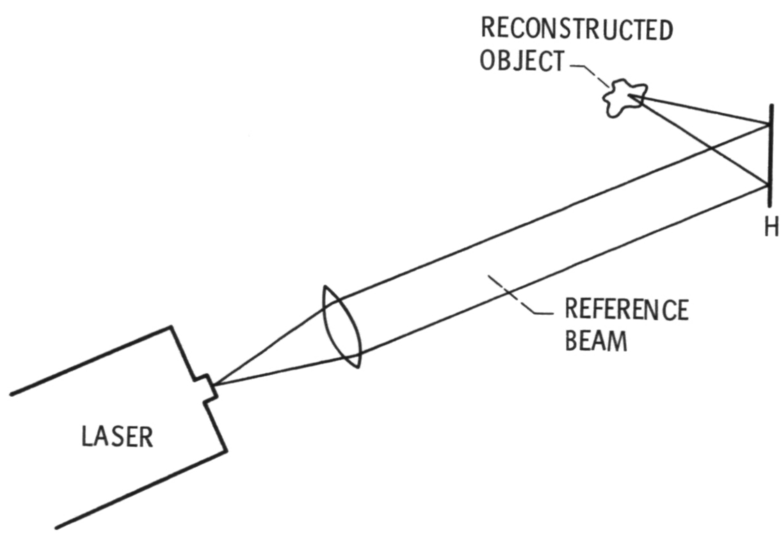

Figure 3. - Viewing a hologram.

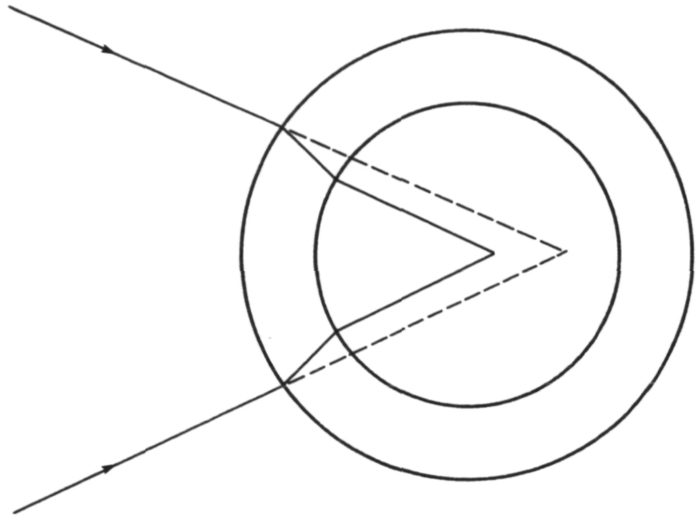

Figure 4. - Misalignment of crossed beams through a curved surface.

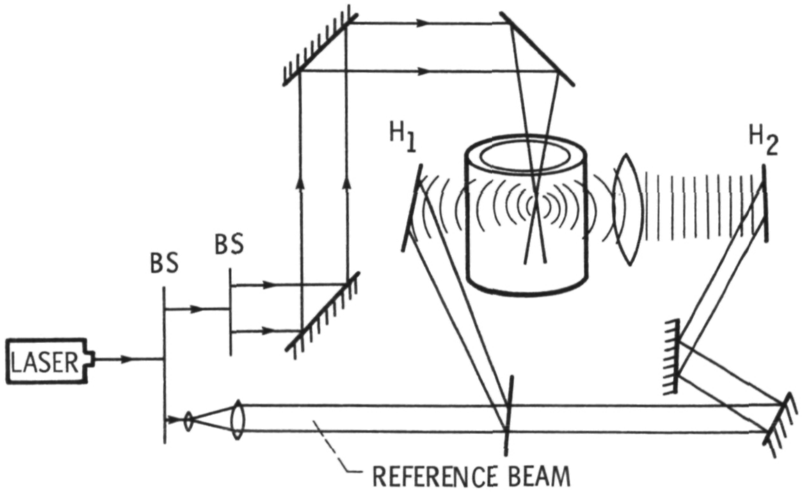

Figure 5. - Constructing correctional holograms.

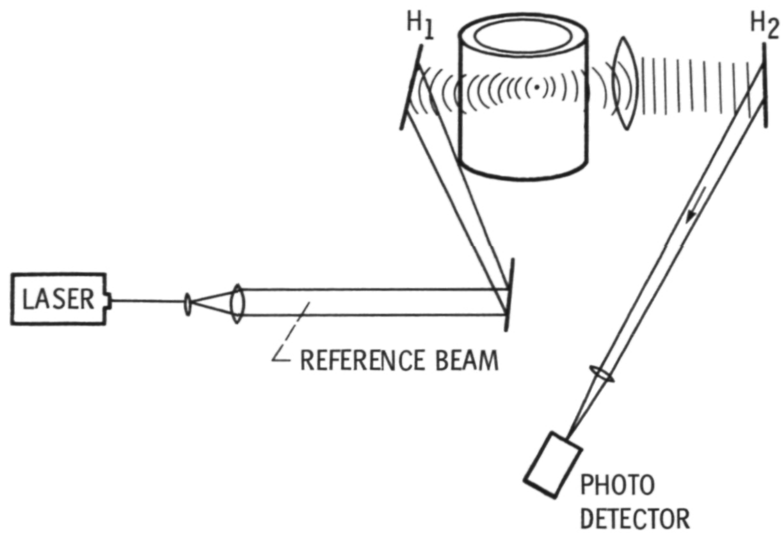

Figure 6. - Viewing correctional holograms.

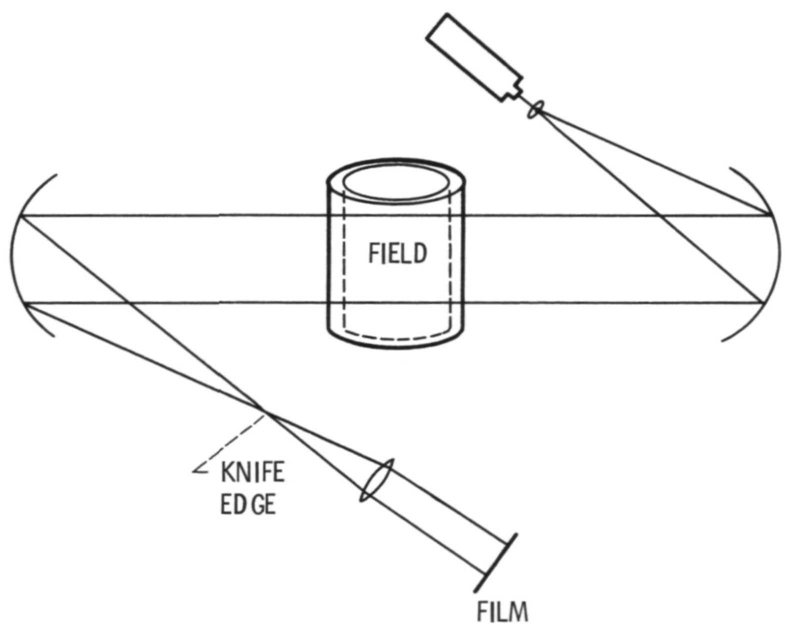

Figure 7. - Schlieren flow visualization system.

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